George WP York, Ph.D., Lt Col, USAF
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FINAL REPORT ON RESEARCH ACTIVITIES AND RESULTS ON THE PROJECT:
«Solar Rotation, Activity and the Interplanetary Magnetic Field: Forecasting the Strength of the Solar Cycle 24»

A) SHORT DESCRIPTION OF THE PERFORMED RESEARCH

Research activities embraced collecting the data (different time series of sunspot numbers and other proxies for the solar activity, positions of sunspot groups from Greenwich and SOON/USAF/NOAA, full-disc 28.4 nm solar images from SOHO-EIT), data reduction (various procedures for the coordinate and velocity determination and statistical analysis) and an interpretation of the results within different theoretical models (dynamo theory and hydromagnetic theory of the solar rotation).

A special software procedure for the determination of the objects' coordinates on the solar disc was programmed (software Sungrabber). Also, an algorithm for the prediction and reconstruction of the solar cycle amplitude was developed using (i) the asymmetry method, (ii) the minimum – maximum method and (iii) the ARMA method.

The research was performed by following researchers: R. Brajša (PI, Hvar Observatory), D. Ruždjak (Hvar Observatory), E. Cliver (AFRL, Hanscom), L. Svalgaard (Easy Toolkit, Inc., Houston), H. Wöhl (KIS, Freiburg), A. Hanslmeier (IGAM, Univ. Graz), G.Verbanac (Geophys. Inst., Faculty of Science, Univ. Zagreb) and D. Hržina (Astronomical Observatory Zagreb).

Up to now the results were presented at three scientific conferences, in two invited talks held at scientific institutes and in three papers, while four additional papers are in preparation.

Summary of results on particular research topics:

1. Solar cycle predictions and reconstructions

1.1. The asymmetry of the ascending and descending solar cycle phases was calculated (Method 1) and used as a proxy for solar activity on longer time scales. The relative sunspot numbers in the epochs of solar activity minima and maxima were correlated (Method 2) and the parameters of an autoregressive moving average model (ARMA, Method 3) were estimated. Also, the power spectrum of data obtained with the method 1 was analysed and the Methods 1 and 3 were combined. Signatures of the

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Solar Rotation, Activity and the Interplanetary Magnetic Field: Forecasting the Strength of the Solar Cycle 24

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Dr. Roman Brajsa

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Faculty of Geodesy
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12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking Faculty of Geodesy as follows: Present status:
A prediction of the strength of future solar cycles is not an easy task (e.g., Wilson, 1994, Solar and Stellar Activity Cycles, Cambridge Univ. Press; Hanslmeier, Denkmayr, and Weiss, 1999, Sol. Phys. 184, 213). There are currently two principal predictions of the strength of the next solar cycle (no. 24). The first one forecasts that the next solar cycle will be stronger than the last one. This prediction is based on a flux-transport dynamo model (e.g., Dikpati and Gilman, 2006, ApJ 649, 498; Dikpati, de Toma, and Gilman, 2006, GRL 33, L05102). The second prediction forecasts a smaller strength of the cycle no. 24 than was the no. 23. It is based on observations of polar magnetic fields on the Sun and the secular trend of the IMF (Svalgaard and Cliver, 2005; Svalgaard, Cliver, and Kamide, 2005, GRL 32, L01104). This prediction is consistent with the statistical analysis of long-term variability of solar activity (Solanki et al., 2004, Nature 431, 1084).
  Recently, Brajsa, Ruzdjak, and Woehl (2006, Sol. Phys. 237, 365) investigated temporal variations of the solar rotation determined by sunspot groups in the years 1874-1981. They have used the data set of sunspot groups' positions recorded at Greenwich (1874-1976) extended by the measurements provided by the Solar Optical Observing Network (SOON) of the US Air Force and the National Oceanic and Atmospheric Administration (NOAA) for the years 1977-1981. The residual method of Gilman and Howard (1984, ApJ 283, 385) was used. This method yields a single number for each year describing the average deviation from the mean value of the solar rotation. A dependence of the rotation velocity residual on the phase of the solar cycle was found as well as a secular deceleration of the observed solar rotation contemporary with the well-known increase of the solar activity.

15. SUBJECT TERMS
EOARD, Space Weather, Solar Physics

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Maunder, Dalton and Gleissberg minima were found with Method 1. A period of about 70 years, somewhat shorter than the Gleissberg period was identified in the asymmetry data. The maximal smoothed monthly sunspot number during the Maunder minimum was reconstructed and found to be in the range 0 - 35 (Method 1). The estimated relative sunspot number of the next solar maximum is in the range 95 - 109 (Method 2). Method 3 predicts the next solar maximum between 2011 and 2012 and the next solar minimum for 2017.Also, it forecasts the relative sunspot number in the next maximum to be 90 ± 27. A combination of the Methods 1 and 3 gives for the next solar maximum relative sunspot numbers between 78 and 99. The asymmetry parameter provided by the Method 1 is a good proxy for solar activity in the past, also in the periods for which no reliable sunspot numbers are available. Our prediction for the next solar cycle no. 24 is that it will be weaker than the last cycle no. 23.
(Brajša, R., Wöhl, H., Hanslmeier, A., Verbanac, G., Ruždjak, D., Cliver, E., Svalgaard, L., Roth, M.: 2008, On solar cycle predictions and reconstructions, *Astron. Astrophys.*, accepted)

1.2. We have also considered the possibility that the commonly used sunspot number series in the last 165 years is not calibrated correctly (Cliver & Svalgaard, 2007, AGU Fall Meeting; Svalgaard & Cliver, 2007, AGU Fall Meeting; Svalgaard, 2008, AGU Spring Meeting). It is interesting, however, that the use of this alternative sunspot number series does not influence significantly the prediction for the next solar maximum using the minimum – maximum method (Method 2).
(Brajša, R., Wöhl, H., Hanslmeier, A., Verbanac, G., Ruždjak, D., Cliver, E., Svalgaard, L., Roth, M.: A prediction for the 24th solar cycle, *Cent. Eur. Astrophys. Bull.* **33**, to be submitted)

2. Solar rotation and solar activity

2.1. Theoretical analysis of the interaction between differential rotation and magnetic field on the Sun was performed by Brun (2004, Sol. Phys. 220, 333) and by Lanza (2007, Astron. Astrophys. 471, 1011). One consequence of these studies is that the Maxwell stresses can oppose the Reynolds stresses, and thus contribute to the transport of the angular momentum towards the solar poles, leading to a reduced differential rotation. So, when magnetic fields are weaker, a more pronounced differential rotation can be expected, yielding a higher rotation velocity at low latitudes on average. This hypothesis is consistent with the behaviour of the solar rotation during the Maunder minimum. We have used the extended Greenwich data set (1878 - 1981) and applied the residual method in the solar rotation analysis. The dependence of the rotation velocity residual (yearly values) determined by sunspot groups is analysed as a function of the solar activity and the interplanetary magnetic field. A secular deceleration of the mean solar rotation in the 20th century, during increasing solar activity, was found by tracing sunspot groups. In the years 1902 and 1913 we have found possible rotational signatures of two weak solar activity cycles (the Gleissberg minimum). The rotation velocity residual increased in these years for about 0.4 degrees per day, in a qualitative and quantitative agreement with a similar rotational behaviour inferred for the Maunder minimum.
(Brajša, R., Wöhl, H., Ruždjak, D., Vršnak, B., Verbanac, G., Svalgaard, L., Hochedez, J.-F.: 2007, On the solar rotation and activity, *Astron. Nachr.* **328**, 1013-1015)

2.2. A qualitative similar behaviour (to the results described in 2.1.) was also found on the shorter time scale during almost the whole solar cycle no. 23. Solar rotation was determined tracing coronal bright points in a series of full-disc solar images taken at 28.4 nm with the SOHO-EIT instrument using an automatic procedure. More than 50 000 velocity values were measured in the period 1998 – 2006 and the activity dependence of the rotation velocity was analysed.
(Wöhl, H., Brajša, R., Hanslmeier, A., Gissot, S. F.: 2008, Solar differential rotation determined by tracing coronal bright points in SOHO-EIT images: Results and comparisons for the period 1998-2006, *Astron. Astrophys.*, to be submitted)

2.3. The analysis of the solar rotation and activity with sunspot groups was continued using the SOON/USAF/NOAA data for the period 1981 to present. We have started to compare the positions of sunspot groups from that data set with the ones from the other data sets (Debrecen, Kanzelhöhe, Kodaikanal) with the aim to check the precision of different measurements. The first test period was chosen to be January – October 1993; this is the declining solar activity phase when sunspots of the Zurich classes H and J, suitable for the unambigous position determination, can be identified. (not published yet, work in progress)

Research planned for the near future:

The results on the solar rotation and activity using sunspot groups for the whole period, 1874 – present, will be published after calibrating various sunspot position measurements and estimating errors. Also, the solar rotation will be reconstructed back to the Maunder minimum combining different methods of data reduction. Finally, (i) an improved prediction for the next solar cycle will be made using final data for the actual solar minimum, (ii) applying a time lag of 3 years before minimum in the minimum – maximum method and (iii) applying the ARMA method on the monthly values.

B) US VISITORS

22-26 September 2008: E. W. Cliver (AFRL, Hanscom)
22-26 September 2008: N. Gopalswamy (NASA, GSFC)

C) PRESENTATIONS AND PUBLICATIONS OF THE RESULTS

1. 3rd Central European Solar Physics Meeting, Bairisch Kölldorf, Austria, 10-12 October 2007:

1.1. Brajša, R., Wöhl, H., Hanslmeier, A., Mulec, M., Skokić, I., Verbanac, G., Hagenaar, H., Ruždjak, V., Hochedez, J.-F.: Velocity field on the Sun determined by coronal bright points, Abstract Book, p. 11-12.

1.2. Brajša, R., Mulec, M., Hanslmeier, A., Wöhl, H., Ruždjak, V., Hochedez, J.-F.: 2008, Coronal bright points as tracers for solar rotation in October-November 1999, *Cent. Eur. Astrophys. Bull.* **32**, 117-124.

2. 12th European Solar Physics Meeting, ESPM-12, Freiburg, Germany, 8-12 September 2008:

2.1. Brajša, R., Wöhl, H., Hanslmeier, A., Gissot, S. F.: On the Solar Rotation and Activity in the Years 1998-2003, Abstract Book, p. 52.

2.2. Brajša, R., Wöhl, H., Hanslmeier, A., Gissot, S. F.: On the Solar Rotation and Activity in the Years 1998-2003, Electronic proceedings, Ed. H. Peter, (http://espm.kis.uni-freiburg.de), Poster 2.3-32

3. IXth Hvar Astrophysical Colloquium: «Solar Minimum Meeting», Hvar Croatia, 22-26 September 2008:
3.1. Brajša, R., Wöhl, H., Hanslmeier, A., Verbanac, G., Ruždjak, D., Cliver, E., Svalgaard, L., Roth, M.: A prediction for the 24th solar cycle, Abstract Book, p. 22.

3.2. Brajša, R., Wöhl, H., Hanslmeier, A., Verbanac, G., Ruždjak, D., Cliver, E., Svalgaard, L., Roth, M.: A prediction for the 24th solar cycle, *Cent. Eur. Astrophys. Bull.* **33**, to be submitted.

4. Invited talks held at scientific institutes:

Brajša, R.: On solar cycle predictions, Solar rotation and activity, Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany, 24 April 2008.

Brajša, R.: On solar cycle predictions, Institute of Geophysics, Astrophysics and Meteorology, Institute of Physics, University of Graz, Austria, 28 May 2008.

5. Papers in refereed journals:

5.1. Brajša, R., Wöhl, H., Ruždjak, D., Vršnak, B., Verbanac, G., Svalgaard, L., Hochedez, J.-F.: 2007, On the solar rotation and activity, *Astron. Nachr.* **328**, 1013-1015.

5.2. Brajša, R., Wöhl, H., Hanslmeier, A., Verbanac, G., Ruždjak, D., Cliver, E., Svalgaard, L., Roth, M.: 2008, On solar cycle predictions and reconstructions, *Astron. Astrophys.*, accepted.

5.3. Wöhl, H., Brajša, R., Hanslmeier, A., Gissot, S. F.: 2008, Solar differential rotation determined by tracing coronal bright points in SOHO-EIT images: Results and comparisons for the period 1998-2006, *Astron. Astrophys.*, to be submitted.

D) FINANCIAL REPORT

Up to now **$16,000** were received and **$15,221** were spent for:

- overhead obligations to the Faculty of Geodesy (10 %)...........................1,600 $
- bank services and health insurance for travels abroad................................349 $
- computer accessories, network equipment and office material..................134 $
- computer repair...1,045 $
- scientific literature (book)..33 $
- visit to KIS Freiburg[1] (R. Brajša, travel expenses)....................................924 $
- visit to IGAM Graz[2] (R. Brajša, travel expenses and accomodation)......6,045 $
- participating at IXth Hvar Astrophysical Coll.[3] (travel expenses and accomodation for R. Brajša and D. Ruždjak)..1,682 $
- labor costs for PI and PhD student...3,409 $

Total...15,221 $

[1]Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany

[2]Institute of Geophysics, Astrophysics and Meteorology, Institute of Physics, University of Graz, Austria

[3]IXth Hvar Astrophysical Colloquium: «Solar Minimum Meeting», Hvar Croatia, 22-26 September 2008

Roman Brajša (PI)